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DEVELOPMENT OF A MICROCIRCUIT GRID TECHNIQUE FOR AUTOMATED CRACK LENGTH MEASUREMENT FOR FATIGUE TESTING AT ELEVATED TEMPERATURE

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A microcircuit grid technique was investigated and used to measure crack lengths in fatigue crack growth test specimens of an aluminum alloy (7075-T6) at room temperature and a nickel-based superalloy (Inconel 718) at 650°C as part of a Phase I SBIR program supported by the Air Force. Crack lengths were determined from stepwise changes in the resistance of microcircuit grids deposited on compact tension specimens by a photolithography process. Crack lengths assessed from discrete voltage changes recorded for a grid on a bridge circuit agreed closely with direct optical measurements. The fatigue crack growth data obtained from both alloys were in agreement with the data in the literature. New innovative concepts for grid design to obtain higher resolution and more uniform resistance changes for the individual grid lines were developed. The advantages of the microcircuit grid technique as compared to other techniques for monitoring crack lengths include: high crack length resolution (better than 5 micrometers), applicability at elevated temperatures by an appropriate selection of conduct-

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ABSTRACT

A microcircuit grid technique was investigated and used to measure crack lengths in fatigue crack growth test specimens of an aluminum alloy (7075-T6) at room temperature and a Ni-based superalloy (Inconel 718) at 650 °C as part of Phase I of a three phase small business innovation research (SBIR) program supported by the Air Force. Crack lengths were determined from stepwise changes in the resistance of microcircuit grids deposited on compact tension specimens by a photolithography process. Crack lengths assessed from discrete voltage changes recorded for a grid on a bridge circuit agreed closely with direct optical measurements. The fatigue crack growth data obtained from both alloys were in agreement with the data in the literature . New innovative concepts for grid design to obtain higher resolution and more uniform resistance changes for the individual grid lines were developed. The advantages of the microcircuit grid technique as compared to other techniques for monitoring crack lengths include: high crack length resolution (~5 μm), applicability at elevated temperatures by an appropriate selection of conducting material for the grids, lack of a need for quantitative calibration of the voltage output, and compatibility for automated data acquisition.

TABLE OF CONTENTS

page

ABSTRACT 3

INTRODUCTION 5

Technical Objectives 8

Research Approach 8

Selection of Test Materials and Fabrication of Test Specimens 8

Deposition of Microcircuit Grids 10

Experimental Arrangement and Procedure for Crack Growth Measurement with Microcircuit Grids 13

RESULTS AND DISCUSSION

Comparison of the Crack Lengths Measured with the Microcircuit Grid and an Optical Microscope 18

Fatigue Crack Growth Results - Aluminum Alloy 19

Fatigue Crack Growth Results - Inconel 718 19

New Design Concepts for Improved Microcircuit Grids 21

CONCLUSIONS 25

REFERENCES 27

LIST OF FIGURES

FIGURE 1 Microcircuit Grid Used to Monitor Fatigue Crack Growth in Aluminum (7075-T6) and Inconel 718 Alloys 14
FIGURE 2 Compact-tension Specimen Configuration Used for Fatigue Crack Growth Experiments 15
FIGURE 3 Bridge Circuit Used to Measure Changes in Resistance of the Microcircuit Grid on Fatigue Crack Growth Specimens 15
FIGURE 4 Comparison of the Predicted (——) and Measured (- - - -) Voltage Change for a Microcircuit Grid on a Fatigue Crack Growth Specimen 17
FIGURE 5 A Comparison of the Crack Lengths Measured with the Microcircuit Grid and an Optical Microscope 18
FIGURE 6 Fatigue Crack Growth Rates for 7075 - T6 Alloy Measured with the Microcircuit Grids 20
FIGURE 7 Fatigue Crack Growth Rates for Inconel 718 Measured with the Microcircuit Grids 21
FIGURE 8 TheModified Grid Design for Obtaining More Uniform Resistance Changes 23
FIGURE 9 Resistance Changes for a Conventional Parallel Microcircuit Grid 24
FIGURE 10 Resistance Changes for the Improved Microcircuit Grid 24
FIGURE 11. A Microcircuit Grid with Variable Line Widths Designed to ObtainUniform Resistance Changes 25
FIGURE 12. A Scheme for Automation Using a Constant Voltage Source 26

LIST OF TABLES

TABLE 1. Dimensions of the Compact Tension Specimens of 7075 - T6 and Inconel718 Alloys Used in Fatigue Crack Growth Tests 9

INTRODUCTION

Accurate prediction of the fatigue life of structural components requires fatigue crack growth rate data for the component materials under conditions representative of their service environments. The continuing development of new structural materials such as advanced superalloys, the new class of intermetallic compounds such as Ti_3Al and Ni_3Al, and advanced ceramics for elevated temperature applications has placed new demands on crack length measuring techniques. The requirements include not only high-temperature capability, but also accuracy, sensitivity and ability to adapt the technique to automated data acquisition. Automated data acquisition with computer interfacing in prolonged fatigue testing can lead to significant savings in manpower costs.

Of the many techniques that have been developed for measuring crack lengths, the following four have been commonly used in fatigue crack growth rate measurements(1) :

(a) optical measurements,
(b) compliance methods,
(c) electrical potential techniques, and
(d) crack-gauge techniques.

Direct visual measurements of crack lengths using a low power optical microscope is the oldest and most common method used to measure crack lengths during fatigue testing. Optical measurements are, however, difficult at elevated temperatures in the presence of furnaces or environmental chambers.

The compliance method is one of many indirect techniques that are available for measuring crack lengths. The crack length is calculated from measured deflection of the crack growth test specimen using a relationship between the specimen compliance (deflection per unit load) and the crack length for a given specimen geometry(2). Compliance relationships have been developed for common crack growth specimens by experimental calibration or by analytical or numerical calculations(3). The compliance relationships have to be established at each temperature, however, and deviations from linear elastic behavior due to nonlinear or inelastic deformations at elevated temperatures can introduce significant errors in the calibration.

Both the electrical-potential techniques[4,5] and crack gages[6,7] use measurements of changes in voltage across two leads on the specimen to measure crack lengths. The crack length is calculated from the measured voltage using a calibration of the relative voltage as a function of the crack length. A constant current is passed either directly through the specimen (electrical-potential techniques) or through a bonded or sputtered gage deposited on the specimen (crack gages). Like the compliance method, however, these techniques depend on calibration and the relationship between the output voltage and the crack length can be affected by metallurgical changes in the test specimen during the course of prolonged high temperature tests or from thickness variations in the sputtered gages. A correction may also be required to account for a thermal emf at the junction of the potential lead and the specimen.

Huang and Virkar[8,9] have developed a technique for measuring crack lengths that has potential for application at temperatures up to 1200 °C. The method uses advanced microcircuit technology to deposit a grid of parallel lines of a conductor on the surface of the specimen with an insulating barrier in between. Crack length is measured as a function of time or loading cycles by monitoring discontinuous changes in the resistance of the grid as the individual strips of the grid are ruptured by the advancing crack. The microcircuit grid technique does not require a quantitative calibration since the crack lengths are obtained from the positions of the individual lines of the grid on the specimen surface and the crack tip position corresponding to a particular grid line is detected from an abrupt change in the resistance of the grid. Other advantages of the technique include high-temperature capability through judicious selection of the conducting grid material, improved crack length resolution of the order of 5 μm made possible by today's advanced microcircuit technology and adaptability of the technique to computer interfacing and automated data acquisition and analysis. The technique is particularly attractive for monitoring crack growth under spectrum thermomechanical loading and in short crack detection, situations where the conventional techniques would require extensive calibration.

The application of the microcircuit grid technique to measurements of fatigue crack growth at ambient and elevated temperatures was investigated in Phase I of a Small Business Innovation Research Program (SBIR) supported by the U. S. Air Force. The following report summarizes the Phase I technical objectives, the results obtained in Phase I including some new grid design concepts for improved response of the microcircuit grids, and recommendations for further development of the microcircuit grid technique.

Technical Objectives

The Phase I research program had two specific technical objectives. The first objective was to demonstrate the validity of the microcircuit grid technique by using the grids for crack length measurements in fatigue crack growth tests at room temperature. Both the crack lengths measured and the crack growth rates obtained in constant load fatigue crack growth tests on a selected high-strength alloy were to be compared with similar data obtained by direct optical measurements. The second technical objective was to evaluate the microcircuit grid technique for applicability in measuring crack lengths in fatigue crack growth tests at elevated temperatures. A task was also to be initiated in Phase I to investigate the feasibility of using multiple grids to extend the range of crack length measurements without losing the high crack length resolution.

Research Approach

Selection of Test Materials and Fabrication of Test Specimens

Two commercial alloys, an aluminum alloy (7075-T6) and a Ni-based superalloy (Inconel 718), were used for fatigue crack growth measurements using the microcircuit grids. The aluminum alloy was used in fatigue crack growth tests at ambient conditions (23 °C, 45 % relative humidity). The high-strength grade, 7075-T6, was selected because extensive fatigue crack growth data have been collected for this alloy and these data are available in the literature for comparison[10]. Inconel 718 was selected for the high temperature fatigue crack growth tests because it is widely used in structural applications in the aerospace, nuclear and petrochemical industries. Fatigue crack growth data are also available for this alloy at temperatures up to 650 °C and in two different heat treatment conditions[11].

Fatigue crack growth test specimens of the compact tension geometry were machined according to the specifications of ASTM Standard E 647-83[12]. The dimensions of the specimens of the two alloys are listed in Table 1. The dimensions of the specimens satisfied all the size requirements specified in ASTM E 647-83. The aluminum alloy specimens were machined and tested in the as-received heat-treated condition. Inconel 718 was obtained in an annealed condition (annealed at 955°C and air cooled to room temperature). Following specimen fabrication and grid deposition, the Inconel specimens were given a conventional heat treatment which included ageing for 8 hours at 720 °C, furnace cooling to 620 °C, a second ageing hold for 9.5 hours at 620 °C and air cooling to room temperature. This conventional heat treatment was also used to cure the platinum paste used to attach the platinum lead wires to the platinum microcircuit grids on the specimens. Alternatively, specimens were first heat treated and then gold grids were deposited and silver paste was used to attach gold lead wires.

A servohydraulic test machine with a load capacity of 25 kN was used to conduct the fatigue crack growth tests at both ambient and high temperatures. The fatigue crack

Table 1
Dimensions of the Compact Tension Specimens of 7075 - T6 and Inconel 718 Alloys Used in Fatigue Crack Growth Tests.

Alloy	W (mm)	B (mm)	A (mm)	a_n (mm)
7075 - T6	38.1	8.89	9.52	7.62
Inconel 718	26.0	9.00	6.35	6.35

growth tests on the aluminum alloy specimens were conducted at 30 cycles/s at a load ratio, R = 0.1. The peak load was set at a constant value and the stress-intensity range, ΔK, covered 8 to 16 MPa $m^{1/2}$. The output voltage of the microcircuit grid was continuously monitored during the fatigue test using a strip chart recorder. The total number of load cycles applied to the specimen at specific lengths of the crack as detected by the voltage changes on the strip chart were recorded. In some of the fatigue tests, load cycling was interrupted to optically observe the crack and verify its tip position relative to a specific grid line expected from the voltage step recording.

Fatigue crack growth tests on Inconel were conducted at 650 °C in air using a resistance heated furnace. The test frequency was 40 cycles/minute and the load ratio was 0.05. These test conditions were chosen to match those used by James and Mills[11] in their study of the effect of heat treatment and heat-to-heat variations in the fatigue crack growth response of alloy 718.

Deposition of Microcircuit Grids

The following combinations of conductor and insulator materials were used to prepare the microcircuit grids used in this study. Room temperature specimens were prepared using silica for the electrically insulating material and gold for the conductor. The high temperature specimens were prepared with silicon nitride as the insulator; and either platinum or gold were used for conductors.

The procedure for depositing the microcircuit grid on the fatigue test specimens consisted of a number of steps typically followed in a photolithography process. A detailed description of the procedure used to deposit room temperature grids is given below.

1) Surface preparation: Fatigue specimens were successively ground to 800 grit with SiC abrasive papers followed by lapping with one micron diamond paste. Specimens were ultrasonicated in acectone, rinsed with deionized water, and dried under flowing nitrogen immediately prior to sputtering.

2) RF sputtering of silica: The parallel electrode RF sputtering unit[1] was initially evacuated to 10^{-7} torr, then back filled with argon to a pressure of ten microns. A coating of silica approximately one micron thick was sputtered directly on the polished metal surface using a previously calibrated bias voltage and deposition rate.

3) RF sputtering of gold: In the same apparatus used to deposit the silica, a coating of Ti-W approximately 500 Å thick was sputtered directly on to the silica to promote adhesion of the gold to follow. A layer of Au approximately 1000 Å thick was sputtered on to the Ti-W layer.

4) Application of photoresist: The specimen was mounted on a spinner[2] and positive photoresist[3] was dropped from a micropipet on top of the gold layer while the specimen was spun at 2500 rpm for twenty seconds to produce a uniform coating approximately one micron thick.

5) Low temperature bake: The specimen was baked at 90 °C for one half hour to cure the photoresist.

6) Align mask and selective exposure to UV light: In the aligner[4] mask (a glass slide with the grid pattern image printed on its surface) was accurately positioned above the specimen. A thirty second pulse of UV light was shown through the mask to expose the photoresist everywhere except in the shadow of the mask.

7) Develop and rinse: The specimen was dipped in a developer solution[5] for approximately thirty seconds to dissolve the exposed photoresist. The specimen was then rinsed in deionized water and dried under flowing nitrogen.

8) Post bake: The specimen was then heated at 150°C for one hour to further harden the remaining grid pattern image of photoresist.

---

[1]Model 822 Sputtering System, MCR Materials Research Corp., Orangeburg, NY
[2] Model EC101, Headway Research Co., Garland Tx
[3]Microposit, Shipley Inc., Newton MA
[4]Model 2000 Aligner, KasperInc., Madison Hieghts, MI
[5]Developer, Shipley Inc, Newton MA

9) Au etch: The gold was selectively etched from the surface of the specimen except under the protective grid pattern image of photoresist by dipping the specimen in a solution of potassium iodide, iodine, and water in the ratio 4:1:10 (by weight) for approximately thirty seconds. The specimen was then thoroughly rinsed with deionized water to remove residual etchant.

10) Ti-W etch: The Ti-W was selectively etched from the surface of the specimen except under the remaining gold and photoresist by dipping the specimen in a solution of HF-H_2O in the ratio 1:10 (by weight) for approximately twenty seconds. The specimen was thoroughly rinsed with deionized water to remove residual etchant.

11) Removal of photoresist: The remaining photoresist was removed with a stripper solution. Again the specimen was thoroughly rinsed with deionized water.

The processes used to deposit high temperature microcircuit grids were very similar to the process given above. Silicon nitride was deposited in the same apparatus as silica. However, when platinum was used as the conductor, it was deposited by reflected argon beam bombardment in an ion milling apparatus. Also, platinum had to be etched by direct argon beam bombardment in the ion milling apparatus because a suitable etchant solution for platinum was not developed during the Phase I research effort. In all other aspects the room temperature and high temperature grid deposition procedures were identical.

Lead wires were attached to the microcircuit grids with high temperature metal conductor pastes. Initially ultrasonic wire bonding (the traditional technique used in microcircuit technology) was tried to attach lead wires, but the excessively high pressure used in this technique caused the wires to puncture the insulating layer and short circuit the grids to the specimens. Lead wire attachment by wire bonding techniques may be feasible using alternate equipment.

Lead wires for room temperature specimens were prepared using two different gage wires. A twenty five micron diameter gold wire was bonded to the connecting strip of the grid and to a solder tab using a room temperature silver printing paste. A heavier gage copper wire was used to connect the solder tab to the electronic circuit used to measure the resistance response.

The first set of high temperature specimens that were prepared utilized platinum grids and lead wires. The lead wires were bonded to the grids using a platinum paste[1]. This paste required firing to 1000°C to cure and resulted in weakly bonded wires unacceptable for testing. In addition, surface pits developed during the curing cycle, possibly due to rapid quenching allowing grain pop-out. Subsequent application of pastes penetrated the insulating layer ,thereby rendering these specimens unacceptable for testing.

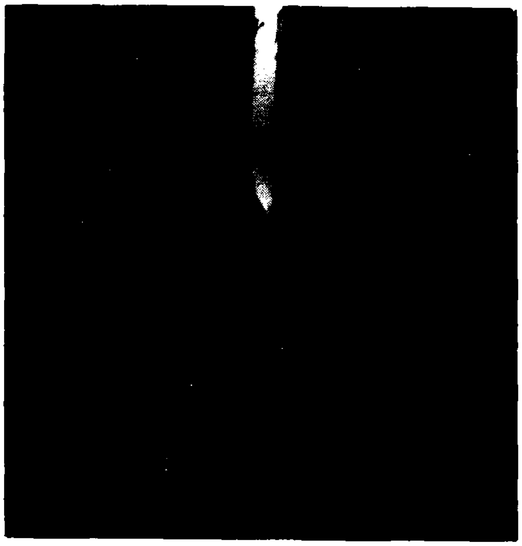
The second set of high temperature specimens were prepared using gold grids and lead wires. A silver paste[2]was used to bond the lead wires to the grid. The lead wires were fifty microns in diameter, these wires were thin enough not to create too much stress at the bond to the grids, but still strong enough to survive specimen installation in the test apparatus. During Phase II, gold and platinum pastes with similar adherence properties as the silver paste used above, will be investigated.

Figure 1 shows the a gold microcircuit grid deposited on a Inconel 718 specimens coated with silicon nitride. Figure 2 shows the ASTM E 647-83 specimen configuration used for fatigue testing.

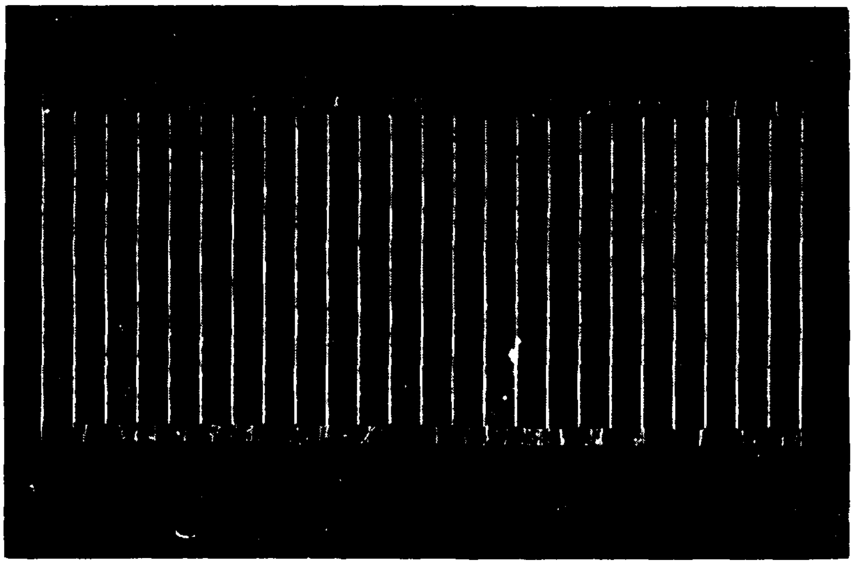
Experimental Arrangement and Procedure for Crack Growth Measurement with Microcircuit Grids

Figure 3 shows the electrical circuit used to monitor the changes in the resistance of the microcircuit grid. Two fixed resistors, R_1 and R_2, a variable resistor, R_v, and the

[1]Product No. CL11-5349, Heraeus Inc., Queen's Village, NY
[2]Product No. C4400-UF, Heraeus Inc., Queens's Village, NY



(a)



(b)

FIGURE 1. Microcircuit Grid Used to Monitor Fatigue Crack Growth in Aluminum (7075-T6) and Inconel 718 Alloys. (a) Specimen with grid. (b) Au grid.

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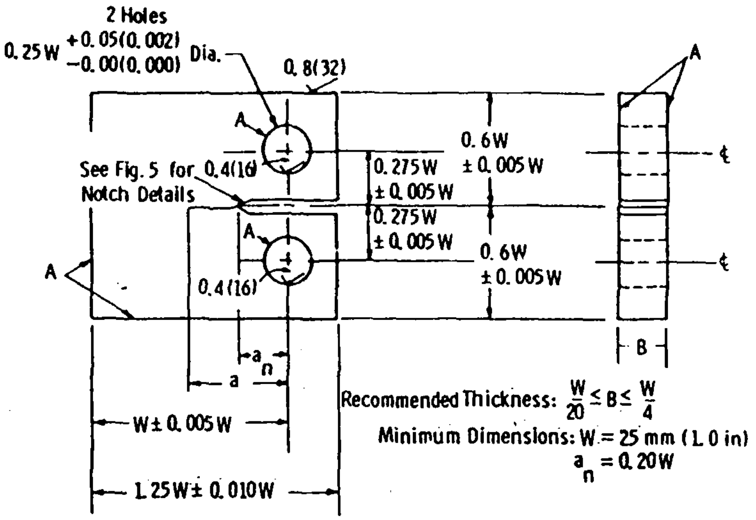

NOTE 1—Dimensions are in millimetres (inches).
NOTE 2—*A*-surfaces shall be perpendicular and parallel as applicable to within 0.002 *W*, TIR.
NOTE 3—The intersection of the tips of the machined notch (a_n) with the specimen faces shall be equally distant from the top and bottom edges of the specimen to within 0.005 *W*.

FIGURE 2. Compact-Tension Specimen Configuration Used for Fatigue Crack Growth Experiments .

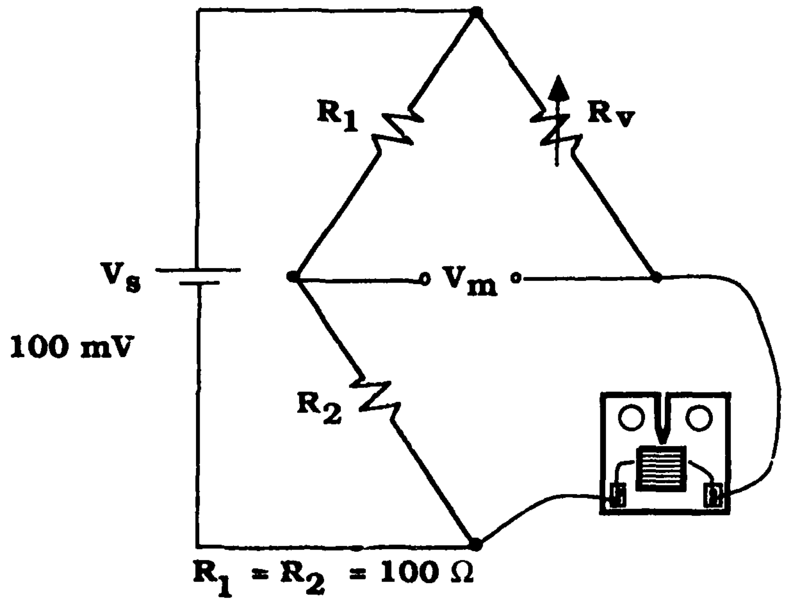

FIGURE 3. The Bridge Circuit Used to Measure Changes in Resistance of the Microcircuit Grid on Fatigue Crack Growth Specimens.

microcircuit grid on the specimen formed a bridge. A constant input voltage, V_S, was applied and the resistance change of the grid was monitored by measuring the voltage, V_M, as indicated in Figure 2. At any stage during crack growth the normalized output voltage is given by the following equation :

$$\frac{V_M}{V_S} = \frac{r}{nR_V + r} - \frac{R_1}{R_1 + R_2} \tag{1}$$

where r is the resistance of the individual grid line and n is the number of unbroken lines remaining in the grid. Two identical 100 ohm resistors with good temperature stability were used for R_1 and R_2. A 0 - 6 volt DC power supply with 0.005 % load regulation was used to supply a source voltage V_S of 100 mV. A ten turn 0 - 100 ohm high stability trim pot was used as the variable resistor. At the beginning of the crack growth experiment, the variable resistor was adjusted to zero the output voltage (i. e., to get $NR_V = r$, where N is the initial number of lines in the grid). As the grid lines were sequentially broken by the advancing crack n decreased from n = N = 25 (i.e., the total number of unbroken lines in the grid initially) to n = 0 with a corresponding stepwise increase in the voltage from zero to 50 mV. Figure 4 compares this output voltage profile for the 25 line grid used in the present study as calculated from Equation 1 with an actual voltage profile measured in an experiment. The profiles are similar but the discrepancy between actual voltage response and the predicted behavior is believed to result from lead wire resistance and current leakage through the specimen. The advantage of the grid technique is that crack position is determined by discrete changes in resistance rather than by absolute resistance.

It can be shown from Equation 1 that the voltage change corresponding to the breaking of the first grid line, $\Delta V = V_M(N) - V_M(N-1)$, is maximized for the following value of the variable resistance :

$$\frac{r}{R_V} = [\, N\,(N-1)]^{1/2} \tag{2}$$

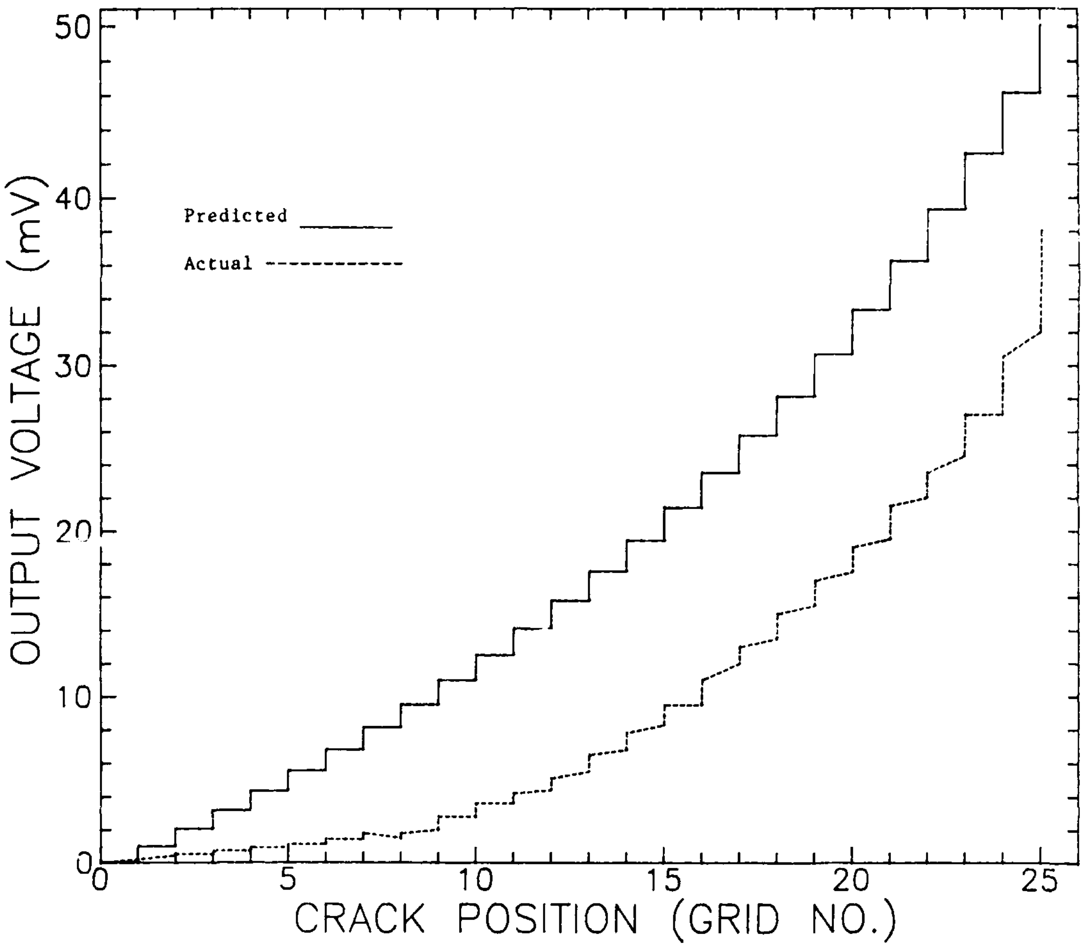

FIGURE 4. A Comparison of the Predicted (——) and Measured (- - - -) Voltage Changes for a Microcircuit Grid on a Fatigue Crack Growth Specimen.

Thus, the variable resistance chosen to null the bridge was also nearly equal to the optimum value to maximize the first voltage step. This condition also evens out the voltage steps for the twenty five lines of the grid.

RESULTS AND DISCUSSION

Comparison of the Crack Lengths Measured with the Microcircuit Grid and an Optical Microscope

Figure 5 shows a plot comparing the crack-tip positions in an aluminum alloy specimen determined from the voltage step recordings and direct optical observations. At each test interruption optical observations confirmed the microcircuit grid measurements; i. e., the crack tip was located at the specific grid line expected from the total number of steps in the voltage recording. The resolution of the optical system was not adequate to determine the crack-tip position relative to the width of the individual grid line. Since it

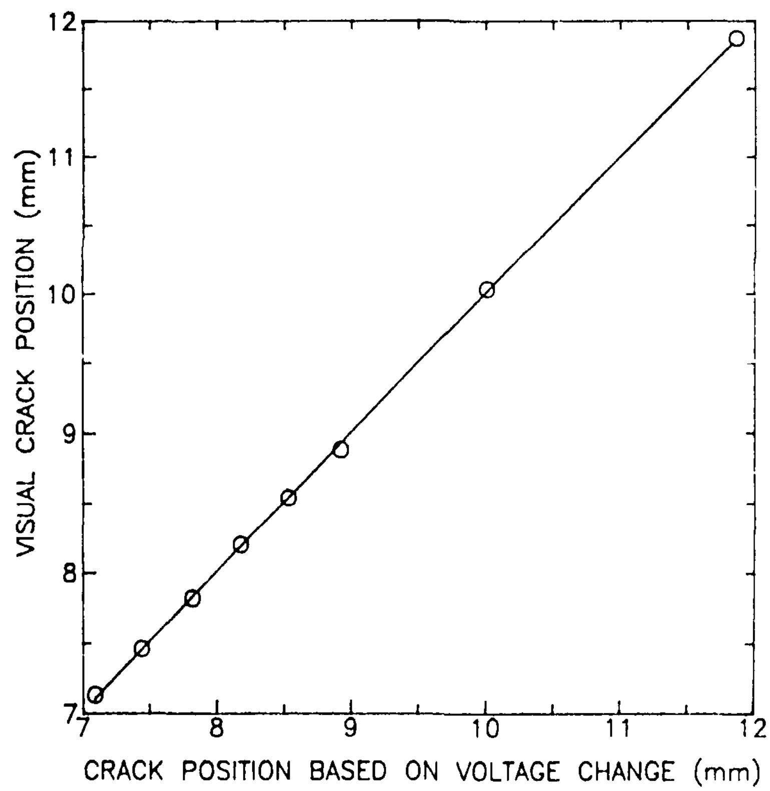

FIGURE 5. A Comparison of the Crack Lengths Measured with the Microcircuit Grid and an Optical Microscope.

can be shown that the voltage step change occurs as the crack severs the grid line (i. e., the voltage increases gradually as the crack advances through the grid line, with a steep rise in voltage as the line is fully severed), it can be concluded that the accuracy of the crack length measurements is better than 5 μm.

Fatigue Crack Growth Results - Aluminum Alloy

Figure 6 summarizes the fatigue crack growth data for the 7075 - T6 alloy. The fatigue crack growth rates, (da/dn), were calculated from the crack length (a) - number of cycles (n) data by fitting a sixth order polynomial as discussed in ASTM Standard E647 - 83. The upper and lower bounds indicated in the figure are from the literature data compiled by Hahn and Simon[10] for identical test conditions. The crack growth rates measured in the present study using the microcircuit grids are generally within the literature data band but are closer to the lower band. This trend is believed to be due to the fact that the frequency of load cycling used in the fatigue tests, 30 cycles/s, was the upper limit of the frequency range covered by the literature data band[10]. This frequency dependence of the fatigue crack growth rate is typically observed in tests conducted in moist environment.

Fatigue Crack Growth Rate Measurements in Inconel 718

Fatigue crack growth rates measured in Inconel 718 at 650 °C using gold microcircuit grids with gold lead wires and silver paste are shown in Figure 7. The data are again compared with an upper and a lower-bound of literature data reported by James and Mills[11]. The data obtained with the microcircuit grids are again within the literature data band. The voltage output response of the microcircuit grid at 650 °C was very similar to that recorded at room temperature. These data show that a thermocouple effect (i.e., the junction EMF at the gold-silver interface) was not a problem and that the microcirciut grid is an excellent method for monitoring crack growth at high temperature.

Inconel 718 specimens with platinum grids were heated to 1000°C to determine the high temperature capability of the grids and the platinum lead wires. Room

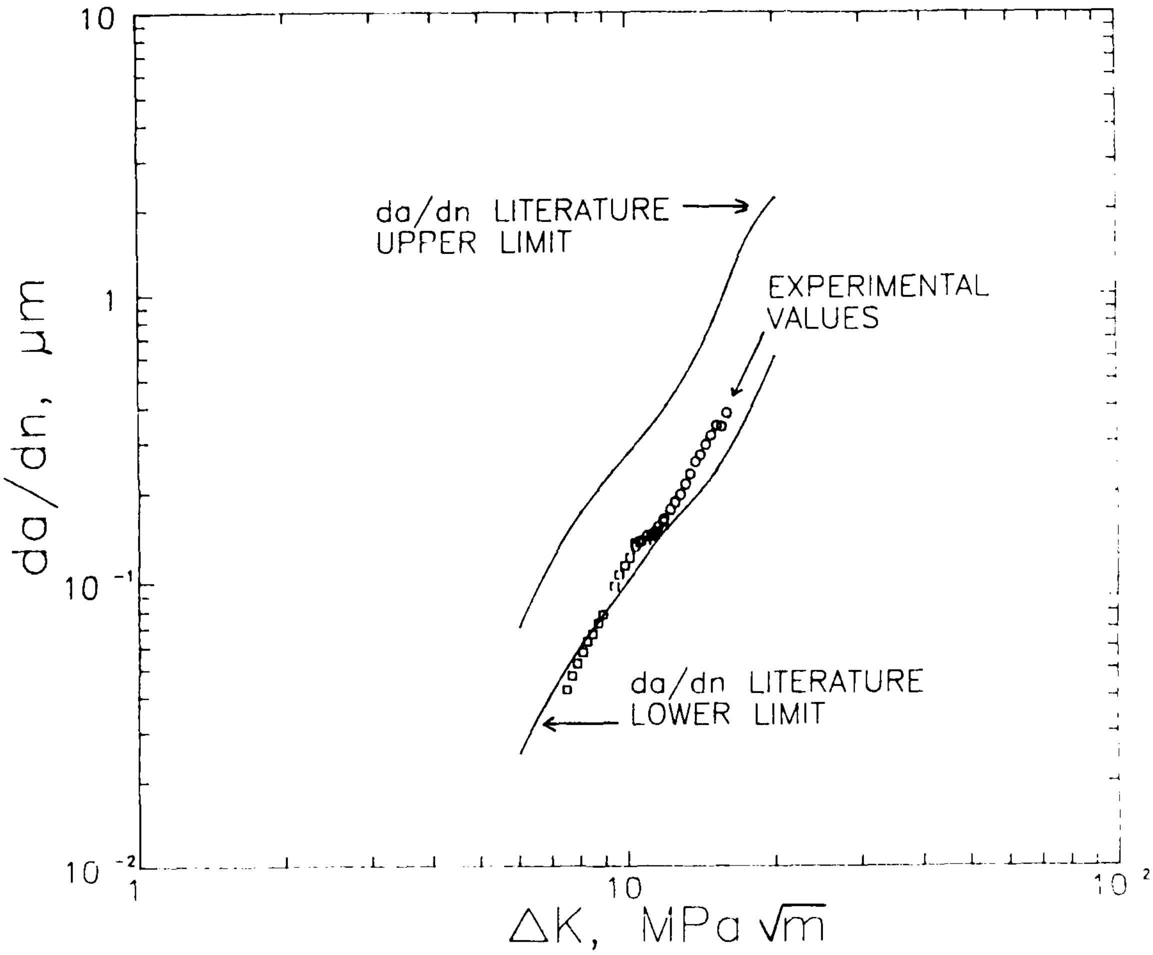

FIGURE 6. Fatigue Crack Growth Rates for 7075 - T6 Alloy Measured with the Microcircuit Grids.

temperature resistance measurements after the high temperature exposure showed that the microcircuit grids and the lead wires can survive temperatures up to at least 1000 °C.

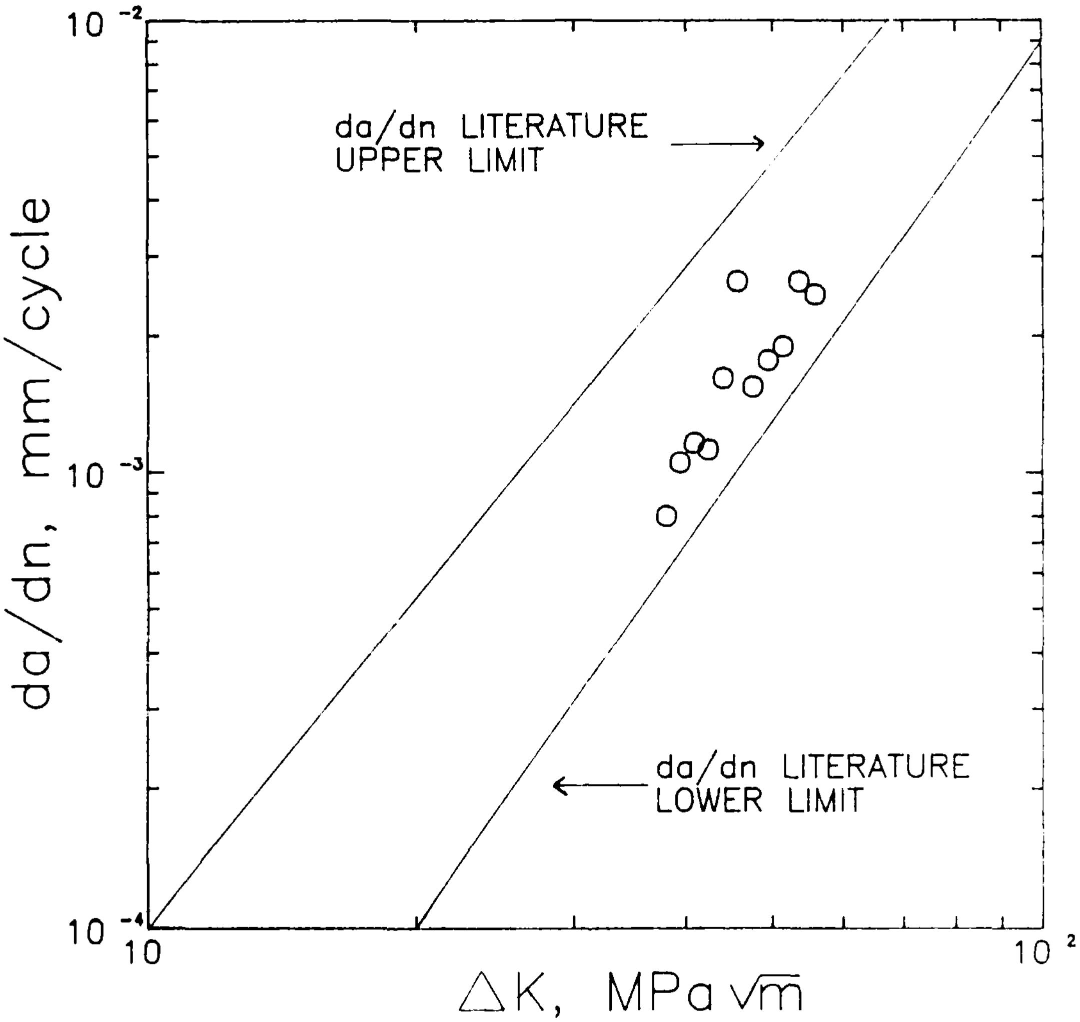

Figure 7. Fatigue Crack Growth Rates for Inconel 718 Measured with the Microcircuit Grids.

New Design Concepts for Improved Microcircuit Grids

The microcircuit grid employed in Phase I covered a total crack length range of 9.4 mm. This was an adequate range for measuring crack lengths in the sizes of the compact tension specimens used. There are many situations, however, where the range of crack lengths would need to be extended while maintaining the crack length intervals and the crack length resolution, or to decrease interline spacing to increase resolution. One option is to increase the number of lines in the same grid. This, however, is not desirable because the resistance change per grid line decreases drastically with increasing number of grid lines in a parallel configuration,therefore a large number of grid lines is likely to introduce errors in detecting crack tip positions. A second option is to deposit multiple grids on the specimen and devise a switching circuit to jump from one grid to the next. This scheme will require one set of lead wires to be connected to every grid on the specimen. Practical difficulties associated with large numbers of wires limit the applicability of this technique.

A new grid design was developed in Phase I which provides significant advantages over the current design. Figure 8 illustrates the design concept. Instead of connecting all the grid lines in parallel, the new grid places in series sets of a small number of grid lines in parallel. The last grid line of each set is receded to the end of the grid pattern in order to avoid an open circuit until the last grid line of the last set is broken. This series configuration allows any number of lines to be put into the grid without changing the voltage step profile for each series set. The series configuration also insures that the magnitude of a step change is of the same order of magnitude as the resistance change for a single broken grid line. The symmetry of the new grid pattern is an essential feature of the design. The last grid line of the first set is the last line of the pattern. The last line of the second set is the second line from the end, and so on. This symmetry minimizes the number of connecting strips.

Figures 9 and 10 show the resistance changes expected for a conventional microcircuit grid and the modified grid, respectively. In both cases the same number of identical grids were assumed. It is evident from the figures that the resistance changes from the new grid design are much more uniform and the total resistance change is about six times that obtained with the old design.

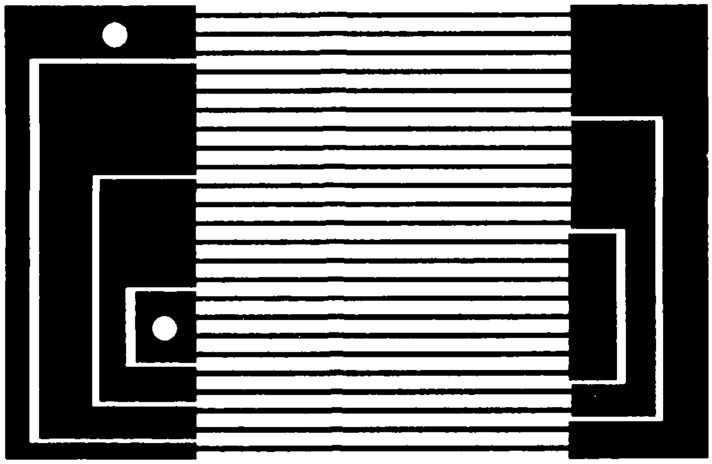

FIGURE 8. The Modified Grid Design for Obtaining More Uniform Resistance Changes.

The resistance of the new grid can be made to change in uniform steps by varying widths of the grid lines within a set so that step changes can be easily detected in a automatic crack length sensing system. This variation of the improved grid design is depicted in Figure 11. Microcircuit grids are particularly well suited for interfacing with a minicomputer. The discrete step change is easily identified and responded to by the use of machine logic. In Phase II a constant voltage source approach will be used to interface microcircuit grids with a minicomputer through a analog to digital converter. The response signal will be scaled to the correct range for the A/D converter with an operational amplifier. Load cycle count will be performed by an electronic counter that is interfaced with the function generator. The cycle count can be read from the electronic counter at any instant by the minicomputer. This data acquisition scheme is depicted in Figure 12.

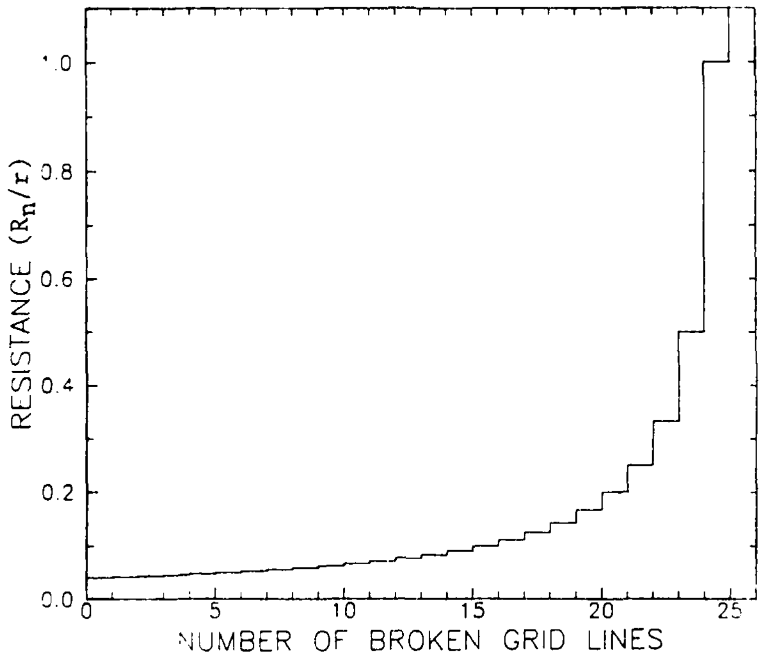

FIGURE 9. Resistance Changes for a Conventional Parallel Microcircuit Grid

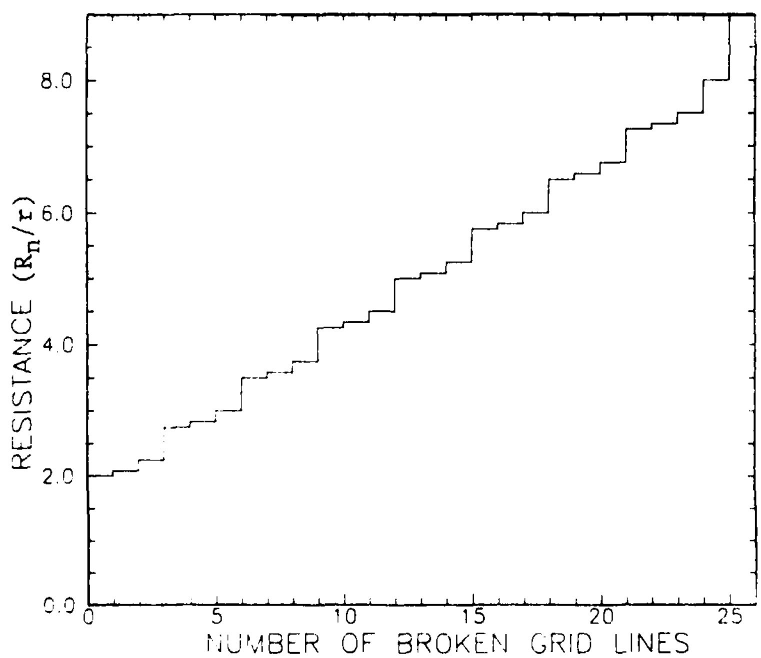

FIGURE 10. Resistance Changes for the Improved Microcircuit Grid.

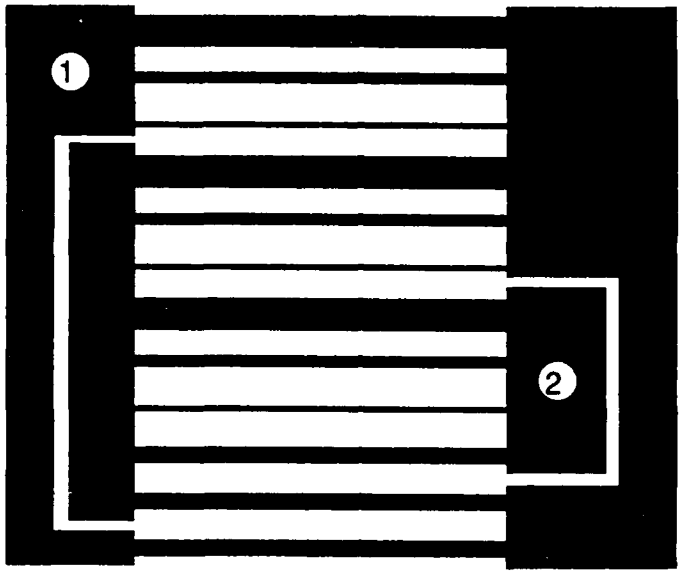

Figure 11. A microcircuit Grid with Variable Line Widths to Obtain Uniform Resistance Changes

A further improvement would be through the use of tracers (grid lines that a characteristically large resistance step changes) to positively verify crack tip position at various intervals. Tracers would reduce problems of losing count or prebroken grid lines.

CONCLUSIONS

The results of Phase I of the program have demonstrated that the microcircuit grid technique can be employed to measure fatigue crack growth at both ambient and elevated temperatures. The most important advantage of the technique is its lack of reliance on a

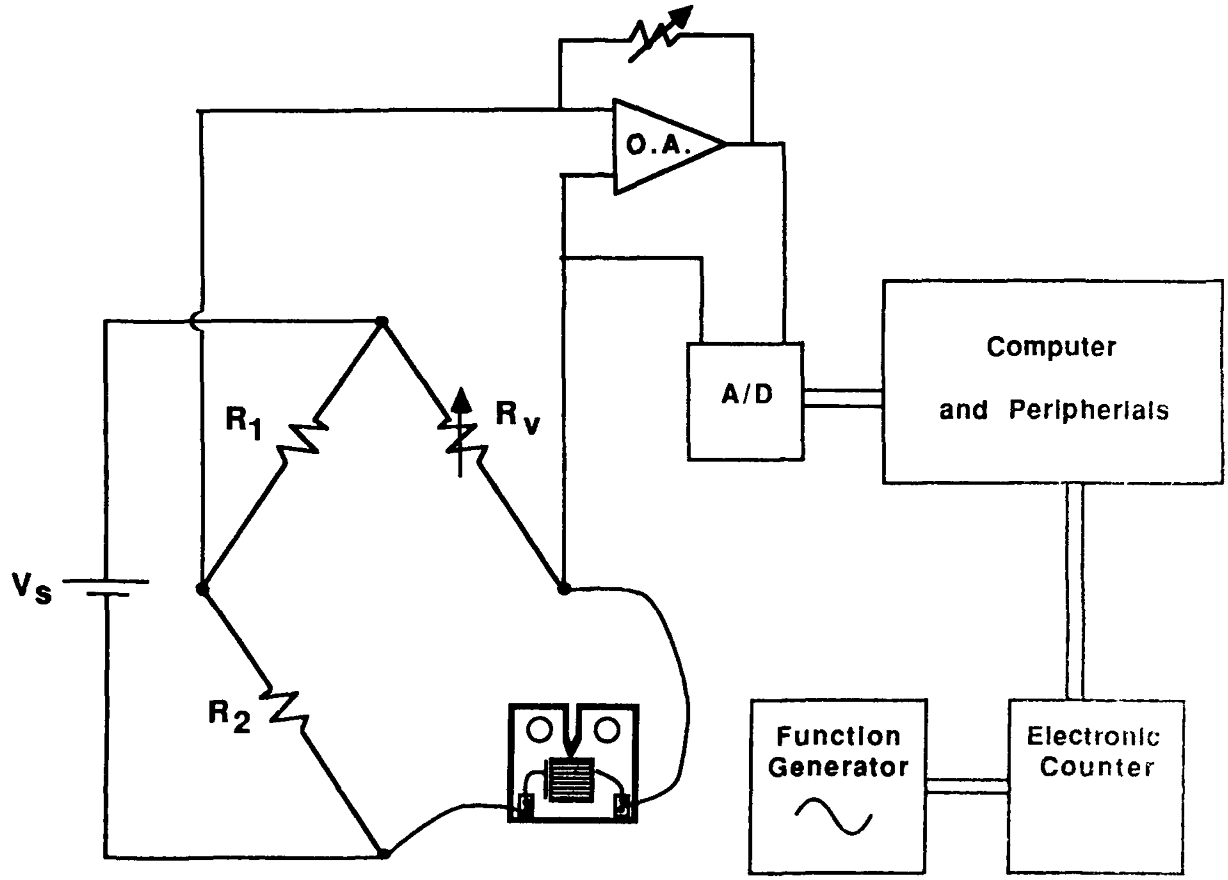

FIGURE 12. A Scheme for Automation Using a Constant Voltage Source.

calibration. Thus, the technique can be potentially employed in time and temperature regimes where metallic structural alloys may exhibit time dependent creep crack growth or significant microstructural changes. Other advantages of the technique include high crack length resolutions that can be achieved with narrow grid lines and capability for interfacing with automatic data acquisition systems. In this regard the modified grid design is particularly attractive. The new design also permits extension of the range of crack lengths that can be measured with the microcircuit grids. This versatility opens a wide range of applications for the microcircuit grids including crack growth measurements in actual load-bearing structures under spectrum thermomechanical loading, a situation where conventional techniques would require extensive calibration.

Although the concept of using the microcircuit grids in fatigue crack growth tests has been proven in Phase I, the results of Phase I have also pointed out the need for improvements in the reliability of the microcircuit grids. It is recommended that a significant level of effort in Phase II be devoted to examining and optimizing each of the different steps in the photolithography process leading up to the deposition of the microcircuit grids. The steps that will require particular attention in Phase II are the initial metallographic preparation of the surfaces of the fatigue crack growth specimens for improved adhesion of the insulating material, the deposition and control of the thickness of the insulating SiO_2 or Si_3N_4 layer to avoid cracking and attachment of the leads. These process improvements should lead to microcircuit grids that are reproducible in their resistance and change in resistance with the number of grid lines. Phase II research should also include fabrication of masks for depositing microcircuit grids of the improved design and interfacing of the microcircuit grid output with a minicomputer for automatic data acquisition and analysis.

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